RAINFALL–RUNOFF RELATIONSHIP OVER ENCRUSTED DUNE SURFACES, NIZZANA, WESTERN NEGEV, ISRAEL

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ABSTRACT

A thin microbial crust covers the lower part of longitudinal dunes in the western Negev, where average annual rainfall is 95 mm. In order to study the effect of the microbial crust on rainfall–runoff relationships under natural rainfall conditions, runoff plots equipped with pressure gauges were established on opposite north- and south-facing slopes that differ in their vegetal cover and crust properties. The study covered four years (1990–94). The first two years were wet and the following two years relatively dry. One to five flow events were recorded per year. No correlation was found between runoff yield, rain amount and rain intensity. Unlike many microbial crusts reported in the literature, the microbial crust in the western Negev is not hydrophobic. Infiltration rate is high under dry surface conditions and of the order of 9–12 mm h^{-1} when the crust is saturated. The high final infiltration rate is explained by the occurrence of large pores that do not seal when the crust is saturated. Typical hydrographs have very steep rising and falling limbs, pointing at a limited contributing area. Most flows last less than 10 min and runoff volumes collected are, on the whole, very small. Owing to differences in crust properties, runoff is higher on north- than on south-facing slopes. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

Loose sand deposits are characterized by a high porosity and a high infiltration rate. This explains why the role of overland flow in landform development of dune fields has been largely ignored. This role was especially overlooked in arid environments, where dune fields are widespread and where rainfall depth in occasional rainstorms is not high enough to initiate runoff in the highly permeable sand. However, information concerning runoff occurrence over sandy areas, although scarce, is available. This information is usually based on occasional field observations and not on systematic studies. The observations relate to a wide range of geographic locations and conditions. De Ploey (1977), Rutin (1983) and Jungerius and van der Meulen (1988) observed and partly monitored runoff generation over the coastal dunes of Belgium and Holland. Dulieu *et al*. (1977) and Courel (1985) observed the same process in Western Africa. Kocurek (1981) observed runoff in the southwestern United States and Hallsworth *et al*. (1982) in Australia. Booth (1941) measured runoff during a sprinkling experiment over sandy soils in the southwestern United States. The areas mentioned above represent humid to semi-arid areas, with annual rain amounts in excess of 250 mm. Runoff development was often explained by the hydrophobic effect of a thin topsoil biological crust which limited infiltration and allowed runoff generation.

A similar crust was observed on dunes in the northern Negev (Danin, 1978; Danin *et al*; 1989; Tsoar and Moller, 1986; Pye and Tsoar, 1987), where average annual rainfall is less than 100 mm. In order to study the hydrological role of this crust under extreme desert conditions, a sprinkling experiment, with a rain intensity of 18·4 mm h^{-1}, was conducted over a small plot covering 1·5 m^2 (Yair, 1990). The experiment was conducted in winter, under wet surface conditions. The sprinkled area responded very quickly. Runoff developed within 3 min, after approximately only 1 mm of rain. Final infiltration rate was of the order of 12 mm h^{-1}. Shortly after this

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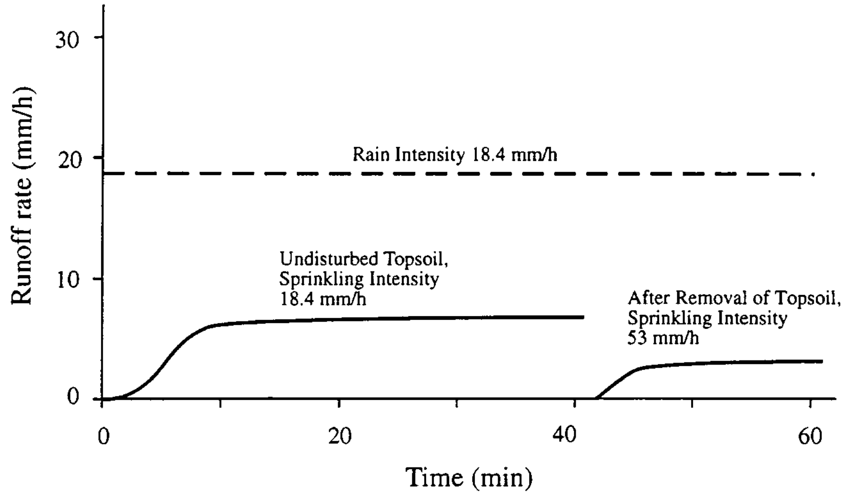

Figure 1. Results of sprinkling experiment

run, a second sprinkling experiment was performed over the same plot after the topsoil crust had been removed (Figure 1). Rain intensity in this experiment was increased to 53 mm h^{-1}. Despite the antecedent wet conditions and the very high rain intensity applied, no runoff was observed for 42 min, by which time the accumulated rain amount reached the high figure of 37 mm. The results of the two experiments clearly demonstrated the importance of the biological topsoil crust in limiting infiltration rate, enhancing runoff generation, and more generally affecting the water regime of the sandy ecosystem considered. Furthermore, during the flow, loose material lying on top of the crust was removed, pointing to the possible importance of erosion by runoff in a sandy environment.

The results of the sprinkling experiment, although interesting, cannot adequately represent the processes under natural rainfall conditions for several reasons.

1. Rainfall was applied with a uniform rain intensity, while natural rainstorms in the area are highly intermittent and characterized by a very high temporal variability in rain intensity. In addition, rain intensites above 12 mm h^{-1} are not very frequent and their duration seldom exceeds a few minutes (Yair and Lavee, 1985).
2. The area covered by the sprinkling experiment (1·5 m^2) is too small to represent processes over larger areas. Field observations clearly show that the extent and thickness of the crust vary with slope aspect and along any given slope.
3. The sprinkling experiment was conducted under wet surface conditions. It does not allow estimation of the hydrological response of the crust under dry surface conditions when the effect of water repellency, caused by the properties of the biological crust, is usually most pronounced (Rutin, 1983; Jungerius and van der Meulen, 1988).

AIM OF THE STUDY

The major aim of the present study was to analyse the frequency and magnitude of runoff, under natural rainfall conditions, in an arid ecosystem of longitudinal dunes. The study is important for our understanding of the redistribution of water resources, of soil development, and of their effect on various biological aspects such as the distribution and composition of the vegetation. In addition, the study is expected to contribute to a better understanding of sedimentary processes taking place within the interdune corridors, extending between two adjoining sand ridges.

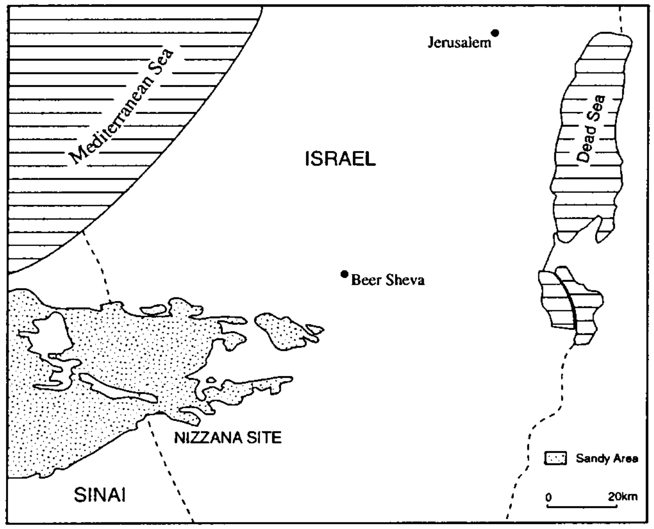

Figure 2. Location map of the Nizzana sand field

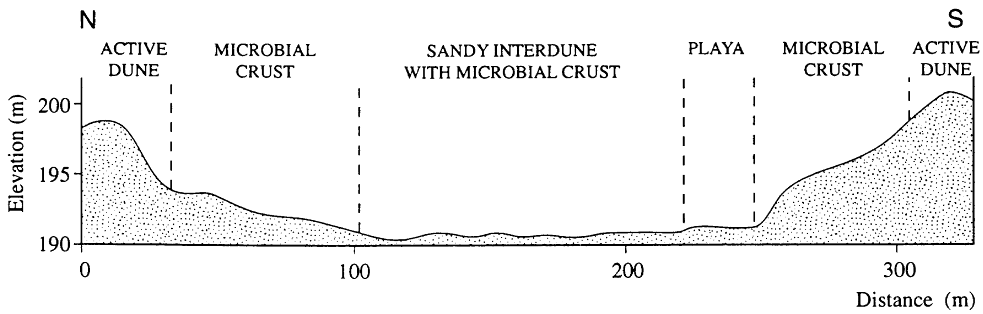

Figure 3. Geomorphic units across the dune system

DESCRIPTION OF THE STUDY AREA

The Nizzana sand field is located at the Israeli–Egyptian border (Figure 2). It represents the eastern extension of the extensive Sinai sandy area. It is characterized by linear dunes trending west–east, separated by wide interdune corridors. Average annual rainfall is 95 mm (Rosenan and Gilad, 1985). The rainy season is limited to the winter months (October to May). Potential annual evaporation is on the order of 2600 mm (Evenari, 1981).

The dune system shows the following subdivisions (Yair 1990; Figure 3).

(A) *The sandy ridge* is composed of two basic units.

(1) *The dune crest* is composed of unconsolidated and mobile sand, sensitive to wind activity, and characterized by a very sparse vegetation cover.

(2) *The basal dune* is characterized by a topsoil microbial crust which, together with the vegetal cover, stabilizes the surface, reducing wind activity. The microphytic crust is composed mainly of cyanobacteria (Lange *et al*., 1992) and contains up to 50 per cent silt and clay as compared to 3–7 per cent in the underlying sand (Yair, 1990).

The properties of the crust vary mainly with slope aspect but also vary from the upper to the lower slope section.

The crust is far more developed over the north- than over the south-facing slopes. North-facing slopes are characterized by a thicker crust, dark brown-green in colour, with a chlorophyll content of

20–50 mg m^{-2}. At the very bottom of the dune slope moss rhizins and protonema are present, enhancing crust aggregation. The crust at the south-facing slope is thinner, with a pale greenish brown colour. Its chlorophyll content is only 15–20 mg m^{-2} (Kidron *et al*., 1995).

The characteristic variations of crust properties along a dune are as follows. The upper part of the encrusted dune is semi-stabilized with a discontinuous crust cover of 40 to 75 per cent of the area. The crust is thin, only 1 mm in thickness and fragile, with a high sand content. At the lower slope section the crust is usually 2–3 mm thick, quite resistant, covering more than 90 per cent of the surface. Similar differences characterize the vegetation cover, which is more extensive on north- than on south-facing slopes (10–40 per cent and 10–30 per cent, respectively). A strip of very dense vegetation is often observed at the sharp transition from steep dune footslope to the almost horizontal interdume surface.

(B) *The interdune corridor* is also composed of two main units.

(1) Flat surfaces, or playas, which are saline and very rich in silt and clay. The playas lack microbial crust and are almost devoid of vegetation.

(2) A sand sheet with sand accumulation around shrubs. This area is covered with a thin microphytic crust and 10–40 per cent vegetal cover.

The soils show a very poor pedogenesis. They were classified as unconsolidated Arenosols over the dune and as Calcaric and Sali-Calcaric Arenosols in the sandy and playa units in the interdune corridor, respectively (Blume *et al*., 1995).

METHODOLOGY

Field setup

The site was equipped with devices for the measurement of rainfall and runoff. Over 50 runoff plots were established in the area in order to answer numerous questions pertaining to the effect of scale, aspect and vegetation on runoff generation and runoff rate. The present paper focuses on rainfall–runoff relationship for relatively large plots, on north- and south-facing slopes, equipped with stage recorders.

Rainfall. Rainfall was recorded with an electronic tipping bucket rain recorder (accuracy 0·1 mm), connected to a data logger.

Runoff. Two runoff plots were constructed on each aspect (Table I and Figures 4 and 5). One plot extended over the entire dune slope, covering crusted and non-crusted surfaces (plots N3 and S2, respectively). The walls of the plots were constructed with a 20 cm high thin metal strip, inserted 10 cm into the sand. All plots were equipped with a V-notch weir and a pressure gauge transducer connected to a data logger.

The plots varied in their area and in their surface properties (Table I). The lower section of plot N3 is characterized, at its lower part, by a hummocky topography of encrusted vegetation mounds, while plot N2 has a smoother encrusted surface. A rugged mound topography is also characteristic of plot S2, while plot S3 had smooth encrusted patches separated by poorly encrusted low mounds.

Table I. Surface characteristics of runoff plots

Plot number	Area (m^2)	Slope angle (degrees)	Perennial vegetation cover (%)	Microtopography and characteristics of stabilized slope section
N2	307	11–17	10	Relatively smooth dark coloured crust
N3	1158 (478)*	6–23	24	Dark coloured crust. Hummocky microtopography of old encrusted vegetation mounds
S2	616 (411)*	6–16	12	Rugged, pale greenish brown crust
S3	198	8–12	15	Smooth, pale greenish brown crust

* Area of encrusted slope section. The vegetation column refers to the encrusted slope section only

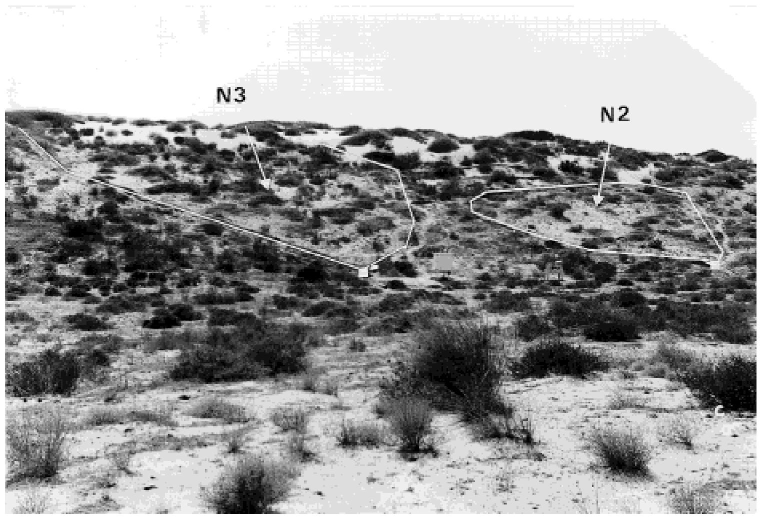

Figure 4. View of north-facing runoff plots (N2, N3)

Figure 5. View of south-facing runoff plots (S2, S3)

RESULTS

Rainfall

The period considered (Tables II and III) is characteristic of the high interannual rainfall variability expected in arid areas. The first two years exhibited rain amounts above average (119·7 and 130·4 mm, respectively), while the two following years were normal to very dry (85·3 mm in 1993 and only 46·9 mm in 1994). Ten to twenty rainstorms were recorded per year (Figures 6 and 7). Most storms belonged to the system of frontal rains originating in the Mediterranean Sea. These rains are usually low in their amount and their intensity (Yair and Lavee, 1985). Approximately 70 per cent of the storms recorded during the period 1990–94 had rain amounts below 5 mm and 85 per cent below 15 mm. Two extreme storms, with rain amounts of 38·8 and 38·5 mm, were recorded in 1990–91. The following year, an extreme rainstorm amounting to 49·8 mm was recorded (Figure 6). In the following dry years, the highest rainstorm recorded in 1993 amounted to 24·2 mm, and in 1994 to 20·7 mm. All other rainstorms, in the last two years, exhibited rain amounts below 10 mm and most often below

Table II. Distribution of rain intensities, 1990–94

Max. intensity ($mm\,h^{-1}$ for 1 min duration)	Rainfall year			
	1990–91	1991–92	1992–93	1993–94
Annual rainfall	119·7	131·4	85·3	46·9
<6	83·1	101·5	65·0	28·1
6–12	21·6	20·5	10·0	10·1
12–18	2·1	2·9	1·0	3·9
18–24	6·6	2·0	0·4	1·6
24–30	1·2	2·0	2·0	0·1
>30	5·1	2·5	6·9	2·2
Total rain amount ≥12 $mm\,h^{-1}$	15·0	9·4	10·3	7·8

Table III. Rainfall–runoff relationship, 1990–94

Rainfall year	Date	Rain (mm)	Max. intensity ($mm\,h^{-1}$) per minute	Runoff volume (l)				Rain amount ≥12 $mm\,h^{-1}$
				Plot N2	Plot N3	Plot S2	Plot S3	
1990–91	24–26/01/91	38·5	36·0	10·8	18·4	–	–	1·7
(119·7 mm)	30/01/91	2·9	12·0	10·7	3·9	–	–	0·0
	7–8/02/91	7·1	24·0	3·8	10·8	0·7	1·8	1·5
	5–6/03/91	22·3	18·0	4·8	8·7	3·1	3·7	0·6
	22–23/03/91	38·8	72·0	243·4	178·3	38·8	74·4	10·3
Annual amount				**273·5**	**220·1**	**42·6**	**79·9**	**14·1**
1991–92	1–3/01/92	49·3	42·0	40·0	29·6	1·4	36·5	3·4
(131·4 mm)	30/1–2/02/92	9·8	18·0	5·0	3·5	–	–	0·8
	6–11/02/92	35·5	12·0	68·6	64·0	9·4	36·2	0·0
	17/02/92	2·1	48·0	61·9	46·9	23·5	37·3	1·7
	24–26/02/92	13·3	18·0	90·8	40·0*	26·0	36·2	0·3
Annual amount				**267·3**	**184·0**	**60·3**	**146·2**	**6·2**
1992–93	11–13/01/93	24·2	12·0	3·5	0·8	1·7	28·3	0·0
(85·3 mm)	12/05/93	9·7	72·0	23·5	8·4	33·1	51·3	8·6
Annual amount				**27·0**	**9·2**	**34·8**	**79·6**	**8·6**
1993–94	21–23/12/93	20·7	54·0	35·1	3·8		12·0	7·1
(46·9 mm)								
Annual amount				**35·1**	**3·8**		**12·0**	**7·1**

N, north-facing slope; S, south-facing slope
* Minimum value due to overflow

5 mm (Figure 7). Except for the very small convective storms of 17.2.92 and 12.5.93, all rainstorms had an intermittent character. The time lapse between consecutive rain showers varied from a few minutes to several hours.

The distribution of rain intensities for the four years considered is presented in Figures 6 and 7 and in Tables II and III. The following points deserve special consideration.

(1) Seventy to 80 per cent of annual rains recorded fell at an intensity of less than 12 mm h^{-1} for the short duration of 1 min only.
(2) Annual rain amount at an intensity in excess of 12 mm h^{-1}, for a duration of 1 min, varied in the range of 7·8 to 15 mm (Table II). These amounts are low, especially if one considers that they were usually recorded for several storms (Table III). Under such conditions, storm rain amounts in excess of 12 mm h^{-1} were, with few exceptions, low to very low (Table III). Furthermore, these amounts were recorded in several rain bursts during the same rainstorm. The highest amount recorded in a single rain burst amounted to 9 mm only. When rain intensities in excess of 30 mm h^{-1} are considered, their frequency is most often much lower, involving negligible rain amounts per storm and per rain burst (Table II).

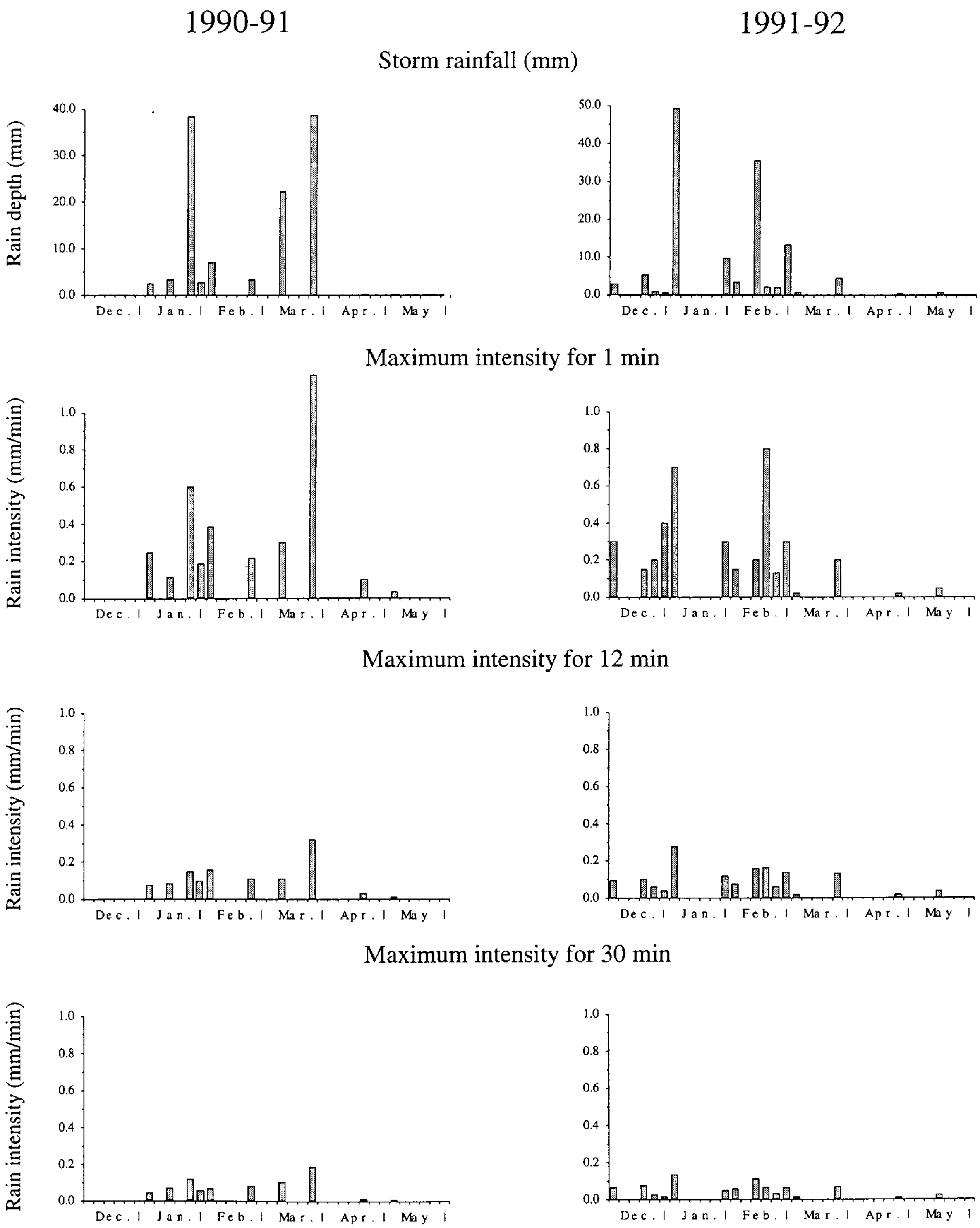

Figure 6. Rainfall years 1990–91 and 1991–92

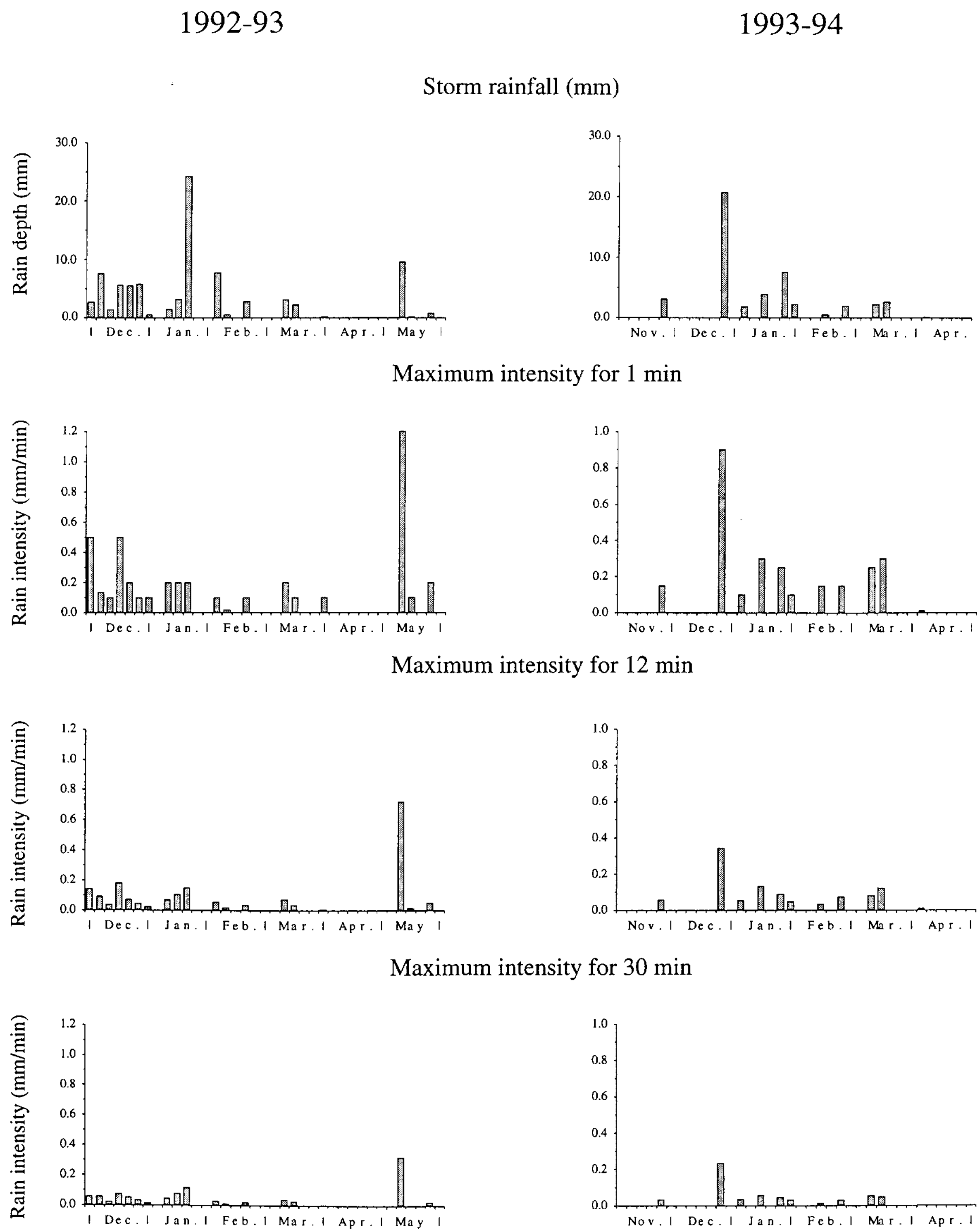

Figure 7. Rainfall years 1992–93 and 1993–94

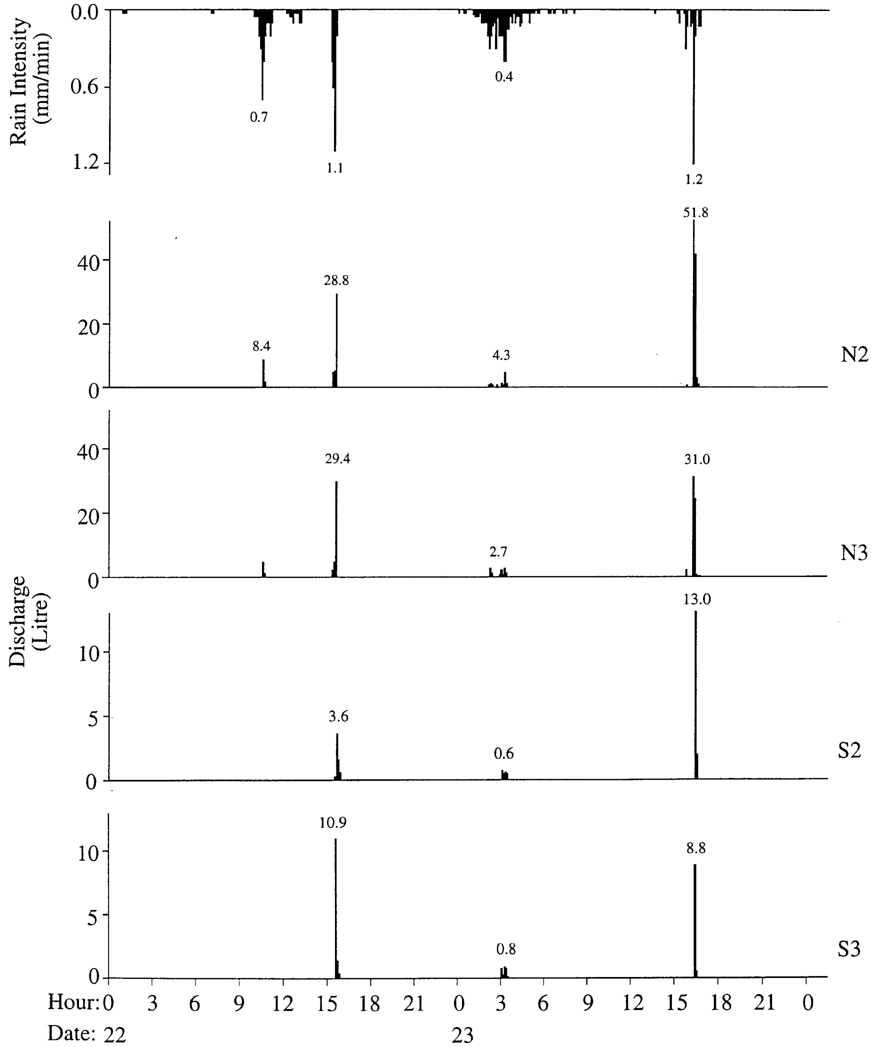

Figure 8. The storm of 22–23 March 1991

Runoff

Runoff data collected during the study period are presented in Table III. The following salient points deserve mention.

(1) Flow frequency was rather high in the rainy years 1990–91 and 1991–92 (with five flow events in each year) but low in the dry years. Only two flows were recorded in 1992–93, and a single flow in 1993–94.

(2) Flow frequency and runoff rates were higher in the north- than on the south-facing slopes during the wet years when low rain intensities prevailed. An opposite trend for runoff rates was observed during some of the runoff-producing storms in 1992–93.

(3) Runoff volumes recorded were on the whole low to very low in view of the area of the plots, rain amounts and peak rain intensities. The highest volumes were collected for the storm of 22–23 March 1991 (Table III). This storm marked the end of a long rainy period responsible for antecedent high soil moisture conditions. The storm itself was quite extreme with 38·8 mm of rain and two rain bursts with peak intensities of 79 and 86 mm h^{-1} for 1 min, the highest intensities recorded during the study period (Figure 8). Despite these extreme conditions, discharge at peak flow, for the most responsive plots, was only 14 per cent of the causative rain burst at plot N2 and 4 per cent at plot S3.

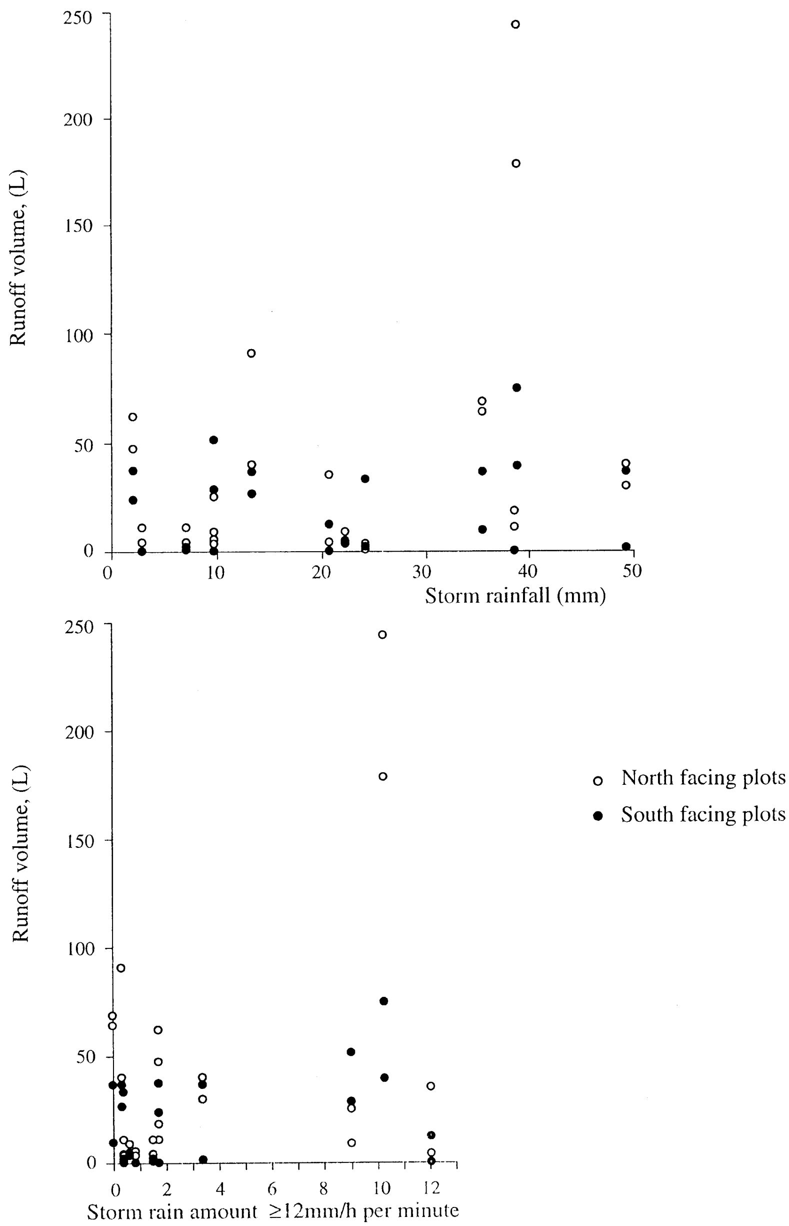

Figure 9. The relationship between storm rainfall and runoff

(4) Data presented in Table III, as well as the scatter diagrams in Figure 9, clearly show that runoff volumes recorded cannot be explained by any of the following variables: storm rain amount, storm peak rain intensity or storm rain amount in excess of 12 mm h^{-1} for 1 min duration. The selection of the latter variable is due to the fact that for most storms a threshold of 9–12 mm h^{-1} was detected for runoff generation. A similar value of final infiltration rate (12 mm h^{-1}) was obtained in the sprinkling experiment (Yair, 1990).

Many of the problems detailed in the previous section are well depicted in the series of hydrographs recorded at plot N1, the most responsive plot to rainfall (Figure 10). All hydrographs have very steep rising and falling limbs, with an extremely short duration that seldom exceeded 10 min.

Another interesting storm is that of 25–26 January 1991 (Figure 11). This was the first important rainstorm of the season. Total rain amount was high, 38·5 mm. The rain was highly intermittent. At the initial part of the

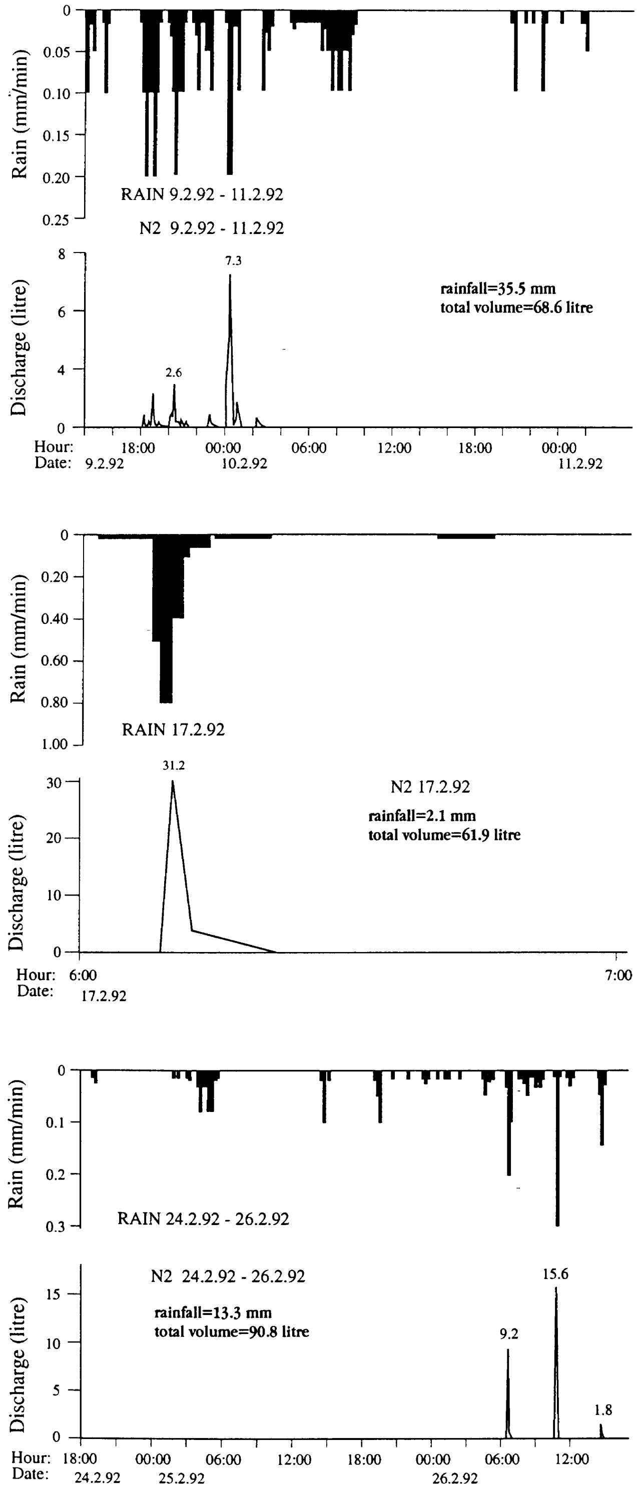

Figure 10. Typical hydrographs at plot N2

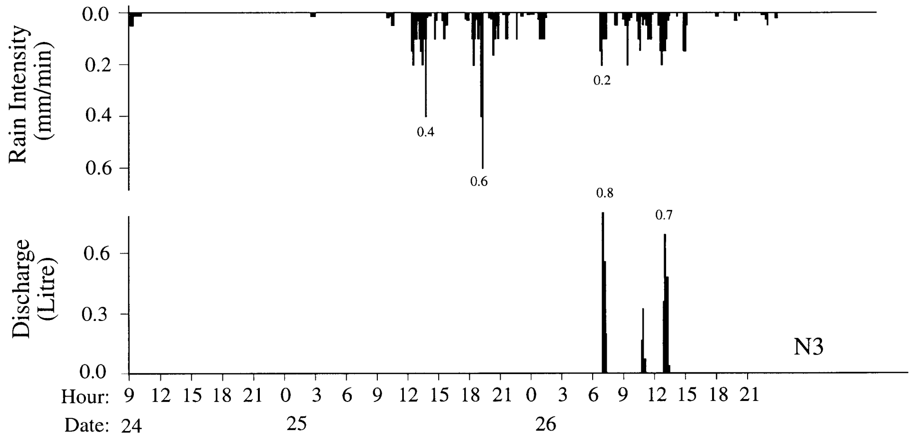

Figure 11. The storm of 24–26 January 1991

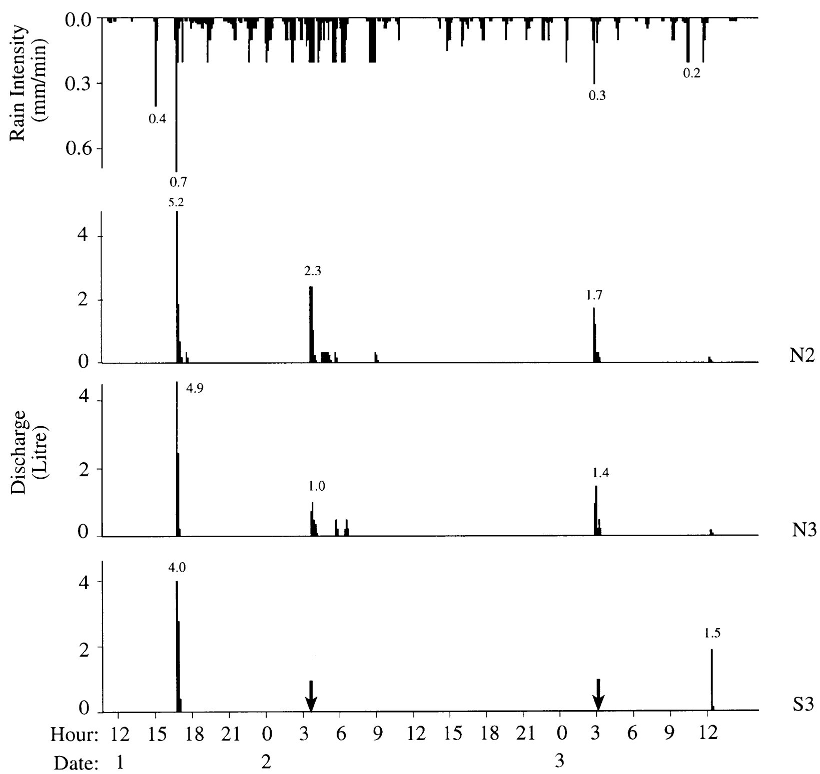

Figure 12. The storm of 1–3 January 1992 (arrows indicate runoff events partially recorded)

storm two high intensity rain bursts were recorded: the first with 26 mm h^{-1} for 1 min and the second with 39 mm h^{-1} for the same duration. Runoff did not develop on any of the plots. However, towards the end of the storm, when rain intensities of 9–12 mm h^{-1} were recorded, several small separate flows developed. Volumes obtained were extremely low (Table III). This is probably due to the very short duration of the effective rain showers and their limited rain amount.

A very similar trend was observed during the storm of 1–3 January 1992 (Figure 12). Once again this was the first storm of the season. Total rain amount was 49·8 mm. A rain intensity of 24 mm h^{-1} was recorded at the very

beginning of the storm with no runoff. Eight distinct short flows developed later on at times when rain intensity reached or exceeded 9–12 mm h^{-1}.

An interesting sequence of events occurred in February 1992 (Figure 10). Two rainstorms, with no runoff, were recorded during the first week of the month with a total rain amount of 13·3 mm and rain intensities below 9 mm h^{-1}. These storms were followed by several storms until the end of the month. The first occurred on 6–11 February. Total rain amount was 35·5 mm. Rain intensities were, on the whole, very low. Peak rain intensity never exceeded 12 mm h^{-1}. However, under the wet conditions that prevailed in the area, very short flows developed at times when rain intensity approximated 9–12 mm h^{-1}. A gradual increase in discharge, for the same rain intensity can be observed during this storm (Figure 10). The second storm occurred on 17 February. Total rain amount for this rainburst was only 2·1 mm with a high intensity of 48 mm h^{-1} for the short duration of 1 min. Despite the low rain amount, runoff developed immediately owing to the high antecedent soil moisture. This result fits the observation made during the sprinkling experiment that when the surface is wet enough, runoff can develop with only 1 mm of rain. The last storm of the month took place on 24–26 February with a total rain amount of 13·3 mm. Rain intensities above 12 mm h^{-1} were recorded towards the end of the storm, resulting in three short flows.

DISCUSSION

The discussion will focus on three questions:

(a) the conditions for runoff initiation;
(b) the extent of the contributing area;
(c) the different response of opposite, north- and south-facing plots.

Conditions for runoff initiation

The lack of correlation between runoff volume and storm rain amount and peak storm rain intensity highlights several aspects.

(1) Loamy and loamy sandy soils are usually considered very sensitive to surface sealing due to the impact of raindrops (McIntyre, 1958; Morin and Benyamini, 1977). Although the topsoil crust in the study area is rich in silt and clay particles (Yair, 1990), such a process did not take place in this specific environment, even at high to very high intensity rain showers. The reason for that is that the topsoil microbial crust is not composed of purely mineral aggregates, held together by chemical and physical bonds, which can crumble under the impact of raindrops. The bonds between the mineral grains are mainly represented here by organic filamentous elements and gels which stick to the mineral particles and are fully resistant to the impact of raindrops. This result agrees with observations by Booth (1941) and Fletcher and Martin (1948) who claim that the thin biological crust, by eliminating the effect of raindrop impact, prevents the rapid development of raincrust conducive to runoff generation. It is interesting to note that in their studies, the biological crust developed mainly on loamy materials amd led to an increase in infiltration and runoff reduction.

(2) Runoff generation over microbial topsoil crusts is often explained by the hydrophobic, water repellent properties of the crust that greatly enhance runoff generation (Bond, 1964; Bond and Harris, 1964; Roberts and Carbon, 1971; Dulieu *et al*., 1977; De Ploey, 1977; Rutin, 1983; Jungerius and van der Meulen, 1988). However, water repellency, in the case of the last two studies, is a temporary property that occurs under dry surface conditions. It disappears once the surface is wet. Using the water drop penetration time test, Rutin (1983) showed, at the Dutch coastal dunes, that the topsoil humic layer lost its water repellency within 30 s to slightly more than 1 min leading, upon wetting, to a gradual increase in infiltration rate.

No repellency was detected at the Nizzana crusts using the water drop penetration time test method (Kidron, 1995). This is further supported by the fact that the crust at Nizzana is capable of absorbing large water amounts when dry. But unlike the coastal Dutch dunes, infiltration decreases with time upon wetting maintaining, once saturated, a relatively high final infiltration rate of 12 mm h^{-1} that only occasionally, under very wet conditions, will reach a lower rate of 9 mm h^{-1} (Figure 10).

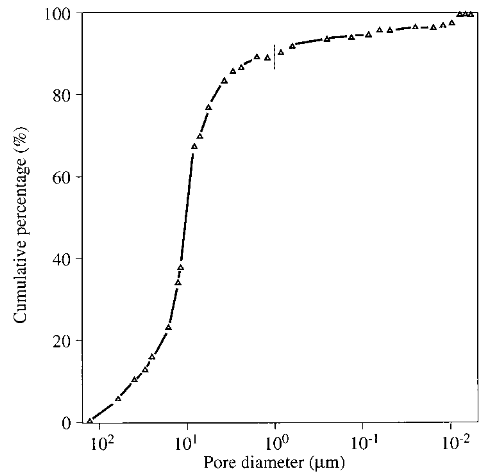

Figure 13. Pore size distribution of the microphytic crust (after Verrecchia *et al*., 1995)

A proper understanding of runoff generation in the area considered requires some knowledge regarding the combined physio-biological processes that take place under wetting conditions. An analysis of the pore size distribution, conducted by Verrecchia *et al*. (1995), shows the large predominance of pore diameters below 40 μm (Figure 13). Upon wetting, two combined processes take place: (a) water absorption and swelling of the silty and especially clayey particles; the latter particles represent up to 20 per cent of the thin crust (Yair, 1990); (b) swelling of the microbial elements. According to Durrell and Shields (1961), Campbell (1979) and Wang *et al*. (1981), the filamentous sheaths may absorb up to 12–13 times their dry weight and increase their volume up to ten times. These two combined processes result in a substantial decrease in crust pore size and infiltration rate. Swelling of the biological elements from 2·5–4 μm to 20–40 μm is sufficient to fill up most of the small voids, significantly limiting water infiltration. However, water can still infiltrate through this membrane, along the larger pores that remain unclogged. The large pores can account for the high final infiltration rate of 9–12 mm h^{-1}

Little is known about the rate of water uptake by biological elements. Campbell (1979), working under laboratory conditions, claims that water absorption by the single species *Microcoleus* requires a few seconds; Wang *et al*. (1981), working under similar conditions, estimate that a period of approximately 30 min is needed to achieve saturation conditions. Data on water uptake time, under field conditions, for composite populations are not available. Results obtained by the present study under natural field conditions indicate that water uptake time, until saturation, is of the order of tens of minutes. It may last several hours under the intermittent rain regime prevailing in the study area. This relatively long period of time explains why, under dry surface conditions, short, high intensity rain showers are unable to initiate runoff. This also explains the lack of correlation between maximum rain intensity and runoff yield. Quite often, high intensity rain showers occur before the crust has reached saturation conditions. On the other hand, the combination of high final infiltration rate and very high frequency of intensities below the threshold for runoff generation is held responsible for the lack of a positive relationship between storm rain amount and runoff yield. Furthermore, one has to keep in mind that the water amount needed to saturate the microbial elements of the thin crust is negligible. The time factor for reaching saturation is thus regarded as far more important than the rain amount. Also of great importance is the fact that, once wet, the microphytic crust can retain its water for a much longer time than non-crusted surfaces. (Verrecchia *et al*., 1995). Field observations, following the rainstorm of 1–3 January 1992, clearly showed that the crust can retain its moisture for many days after the storm and that retention time is longer on north- than on south-facing slopes. Finally, it is quite interesting to note that, as in the present study, no correlation was found by Rutin (1983) between storm runoff and storm rain amount or peak storm rain intensity. The explanation offered by Rutin is exactly opposite to the one proposed here. According to Rutin, runoff developed at any rain intensity and rain amount when the sand was dry; whereas under wet surface conditions runoff generation was inhibited at all recorded rain intensities and rain amounts.

Estimation of the contributing area

Peak flow at the most extreme runoff event (22–23 March 1991, Figure 8), and the most responsive plot (N2), was only 14·2 per cent of the causative rain burst with an intensity of 83·5 mm h^{-1} per minute. This rainburst occurred at the very end of the storm when the microbial crust had already reached saturation conditions, as indicated by two smaller flows recorded earlier. With a final infiltration rate of 12 mm h^{-1}, assuming that the whole crusted area of the plot had contributed runoff, peak flow value should have been 1·19 mm min^{-1}. The record value was, however, only 0·17 mm h^{-1}. The explanation proposed is that the runoff-contributing area did not extend over the whole crusted slope, but was limited to its lower part.

The ratio between peak flow rate and the expected peak flow, had the whole crusted area contributed runoff, may be regarded as an indicator of the contributing area. This ratio (0·17 : 1·19) is equivalent to 14·2 per cent of the drained area. It represents an area of about 40–50 m^2, and a slope length of 7–10 m. The limited contributing area fits very well with the steep shape of the falling limbs of the recorded hydrographs, and especially their very short duration, which rarely exceeded 10 min. Needless to say, the contributing area must have been far more limited at the less extreme storms explaining, together with other factors already mentioned, the low to very low runoff yields recorded. The limitation of the contributing area to the lower part of the encrusted dune slope can also be attributed to differences in infiltration rate along the plot. It has already been mentioned that the thickness and spatial continuity of the crust decrease in the upslope direction with the highest infiltration rate at the upper part of the plot. Finally, one has to keep in mind that differences in infiltration exist not only along the slope, but also laterally, as indicated by the non-uniform response of two adjoining plots with the same aspect (Table III). Such differences are ascribed to microrelief and local density of the vegetal cover. A smooth crust surface can be expected to enhance flow continuity in the downslope direction while a rough surface, with many mounts, depressions and shrubs, would impede this process.

Effect of slope aspect

The data presented in Table III show, in general, a higher frequency and magnitude of runoff over the north- than over the south-facing plots. The explanation proposed is that the microbial crust is less developed and more patchy on the south-facing slopes. As indicated earlier, the biomass content of the microbial crust (chlorophyll, protein and sugar) is two to three times higher at the north- than at the south-facing slope (Kidron, 1995; Kidron *et al*., 1995). In addition, owing to microclimatic conditions, the north-facing slope preserves its moisture for a much longer time.

CONCLUSIONS

The data obtained lead to the following main conclusions.

(1) Unlike many microbial crusts described in the literature, the microbial crust at the Nizzana dune field is not water repellent. It can absorb large rain amounts when dry. Infiltration rate decreases upon wetting until saturation is reached at a rate of 9–12 mm h^{-1}

(2) Runoff yield is not correlated with storm rain amount or peak storm rain intensities. Runoff occurs once the crust is saturated. Such a process requires time. Water uptake by the dry crust, although extremely small, is a slow process under the characteristic regime of intermittent rain prevailing in the area. It may require up to several hours. This explains why high intensity rain bursts at the beginning of a rainstorm, when the crust is still dry, do not generate any runoff, indicating that the sealing process by the impact of raindrops is not relevant on areas covered by a topsoil microphytic crust.

(3) Under the conditions described above, runoff frequency is relatively high (one to five flow events per year), but runoff yields are low to very low. This is due to the very short duration and limited rain amounts of the effective rain showers. This is very well expressed by the short and steep hydrographs. Slope length contributing runoff to the dune base was estimated to be 12 m at extreme flow events and less at most flows.

(4) Runoff frequency and rates were often higher on the north- than on the south-facing plots. This is due to the better development of the microphytic crust on the former than on the latter. Differences in runoff yield

between adjacent plots are explained by their microtopography. Smooth crusted surfaces allow a better flow continuity along the slope than an irregular rough surface with many mounds and shrubs.

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